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MODELLING CLIMATE CHANGE, AND SOME POTENTIAL EFFECTS ON AGRICULTURE IN THE UK

1 Introduction

Agriculture and climate change are no strangers. Trends in the geographical area under cultivation, and changing preferences for one species of cultivar over another can be discerned in the history of the last 3,000 to 4,000 years; some of this evolution can be attributed to slow changes in climate.

What makes the subject of particular interest today is the unusual speed with which the world's climate may change due to industrial emissions, to ploughing up grasslands, and to deforestation. Some predictions foresee changes taking place over the space of a generation which, in pre-industrial times, made their appearance only over centuries or millennia.

If we can be sufficiently sure of the way in which a changing climate will evolve, the appropriate preparations can be made: suitable cultivars can be developed, sea defences can be strengthened and expected changes in land use assimilated into long-term planning. At the moment, however, there are very few aspects of climate change which can be reliably predicted, and even then it is not clear what effect those changes will have. Scientists working in this field learn to view with caution both their own and others' predictions. Unfortunately, some areas of the popular and of the scientific press prefer sensation to science. "Major cities swamped by 2050" attracts more readers than "Scientists sceptical about predictions of 5 metre sea-level rises".

Climate change can occur for a variety of reasons. Long-period oscillations in the sun's heat output, or in the orbit of the earth around the sun, or in the tilt of the earth's axis of rotation, may have caused major climatic upheavals in the past. Large volcanic eruptions can cast a mantle of ash high into the atmosphere causing

global cooling over a few years. Today, however, attention is focused on 'the greenhouse effect', a term used to describe the way certain atmospheric gases act as a heat-retaining 'blanket' over the earth. In this paper an attempt is made to provide a simple statement of what the greenhouse effect is and how it appears likely, on the basis of present evidence, to affect the climate and agriculture of the British Isles.

2 Greenhouse Mechanisms

The greenhouse effect is not new: it has been keeping the earth warm for billions of years. We can demonstrate the extent of the effect with the help of some basic physics.

The earth gains energy from the sun and radiates energy to space. Everything with a temperature above absolute zero (-273°C) radiates energy, not just things that feel "hot"; even a one cubic centimetre ice cube in the freezer is radiating energy at a rate of about 0.2 Watts.

The principle of Conservation of Energy tells us that on average a very precise equilibrium is maintained between heat received by the earth and heat lost to space. Knowing the sun's output, along with geometrical factors such as distance from the sun and the radius of the earth, and the fraction of sunlight reflected from the earth, allows us to accurately calculate the energy received. 'Stefan's Law', formulated almost 100 years ago, relates the radiative energy emitted by a body to its geometry and to its surface temperature. Applying this to the earth yields the result that, in the absence of an atmosphere, the global mean surface temperature would be a chilly -18°C. Fortunately, our atmosphere acts like a blanket interposed between ourselves and space, and its effect is to raise global mean surface temperature to a more tolerable average of around 15°C. Thus, the greenhouse effect makes life possible.

The radiation emitted at the earth's surface ('terrestrial radiation') spans a range of wavelengths typically from 3 to 100 micrometres. Greenhouse gases, of which the most important are water vapour and carbon dioxide, exert their effect by intercepting radiation from the earth's surface. The gases re-emit the energy randomly in all directions and the law of averages dictates that half will be sent downwards, so retaining heat near the surface. Greenhouse gases do not absorb all wavelengths equally; in particular wavelengths between approximately 8 and 14 micrometres are only weakly absorbed, and energy in this band can in the absence of clouds escape freely to space. This band is called the 'atmospheric window' and it happens to contain the 10 micrometre wavelength at which terrestrial radiation is at its most intense. The existence of the atmospheric window is the reason why energy can radiate freely to space on crisp, clear nights allowing ground temperatures to fall rapidly.

The anxiety about additional greenhouse gases arises because they have the potential to alter the existing balance between heat retained by the atmosphere and that allowed to escape freely into space. Of these additions the most important, contributing about 60% of the projected increase in temperature, is carbon dioxide (CO_2). Here Man is adding to an already large effect; initially this addition was for the most part through destruction of forests. However in recent decades the burning of fossil fuels, long stored deep below the earth's surface, has become the dominant source of CO_2. Other important contributions come from methane (about 25%) and the CFC gases (about 10%); the latter, widely believed to be responsible for the ozone hole (an issue separate from climate change) are new greenhouse gases whose importance lies in the fact that they absorb strongly in the currently transparent atmospheric window.

Before leaving greenhouse mechanisms we must note that, whilst greenhouse gases interact with certain components of the terrestrial radiation spectrum, there is already one common ingredient of the

atmosphere which is able to prevent any surface radiation escaping to space, and that is clouds. Clouds, formed of liquid water rather than water vapour, interact with all radiation which comes their way. An overcast sky acts like a reflective blanket, able to dispel mist or to stop an imminent frost in its tracks. Clouds therefore play an important role in deciding how the greenhouse effect will develop; research must try to estimate changes in average cloudiness that might accompany changes in global temperature.

Clouds become even more important when one remembers that while they radiate heat back to earth, they also reflect sunshine. The chill experienced when a bright morning sun is obscured by a lone cloud shows that clouds can also have a cooling effect. Which effect will dominate? For the scientist examining climate change, clouds present the most important and, at the same time, the most difficult of the problems to be solved.

3 Climate Models

The radiative properties of the greenhouse gases are known very precisely. The radiation spectrum of the earth and of the sun are also known very precisely. The radiative properties of clouds have been studied for several years. Given this information, why cannot meteorologists calculate and agree precisely what the greenhouse effect will be? Unfortunately it is not so straightforward. Radiation is not the only type of energy exchange occurring in the atmosphere; large scale movements of air and sea play a major part in the distribution of heat around the globe, and the oceans represent huge potential storehouses not only of heat but also of CO_2. How can we arrange the various pieces of this complex jigsaw?

First of all, we can try to learn from the past, using temperature observations taken over the last 100 years or so. It is not easy to combine all the available data in such a way that a true global average is attained, but the data in Fig. 1 have been painstakingly

compiled, taking account of changes in observing procedures and in the distribution of observing stations over the years. Looking at the underlying trend, the global mean surface temperature has increased by 0.5°C since 1900. Does this trend correspond to a greenhouse warming, and is it safe to extrapolate it forward another 80 years?

Certain features of Fig. 1 make this a dangerous assumption. There is considerable inter-annual and inter-decadal variability in the observed record and a period of cooling from 1940 to 1970 in spite of this being a period when the rate of emission of greenhouse gases was on the increase. Also, recent years have seen a cooling over northwest Europe (not shown in Fig. 1). The most that we can say is that the observed warming this century is not inconsistent with an enhanced greenhouse effect; we cannot say that it has been definitely detected.

Geological evidence suggests that high levels of CO_2 have occurred at previous times in the earth's history (perhaps as a result of volcanic activity) but too little is known about the other circumstances at the time to draw any clear conclusions. The problem is also too complex to try to examine in the laboratory; it is simply not possible to construct a physical model of the atmosphere that would contain all the important features. The only solution is to use a mathematical model in which what is known and understood about the atmosphere is expressed as mathematical equations. Models of the atmosphere usually involve such a large amount of data and so many calculations that they require very large computers.

In climate and weather forecasting models temperatures, winds, sea currents and other variables in the atmosphere and ocean are represented on a three-dimensional array of points; in the horizontal this array follows lines of constant latitude and longitude, while in the vertical they subdivide the ocean and atmosphere each into typically ten layers. Because of the large

computing requirements, the horizontal resolution used in CO_2 experiments has been limited to about 5° of latitude; this gives only a poor definition of regional changes and it is clear that future series of experiments will need to be on a finer mesh.

To make a climate simulation the procedure is much as is used in numerical weather forecasts: an initial state is defined by inserting actual observations of the atmosphere; the laws of physics are solved in order to calculate the initial rate of change. This allows estimation of the state at the end of, say, 10 minutes. The calculation is then repeated to advance a further 10 minutes, and so on until the required time period is completed. For a weather forecast this may be five days. If the model is run further, the forecast of individual events (i.e. what will happen on a particular day) soon becomes poor, but if the model is good enough anticyclones and depressions will continue to develop and move in a realistic fashion. By running for several 'years' a realistic simulation of climate can be obtained. If some aspect is changed such as the amount of CO_2, the climate with increased CO_2 can be simulated and so the climatic response can be estimated.

There is no single model which is used by all climatologists. Everybody would like to include every known process and interaction in their model but today's computers, powerful though they are, are still not powerful enough to do this. So simplifying assumptions are made and the least important interactions are omitted in order to fit the size and power of the computer available. Also, where little is known about a particular process, different scientists naturally differ in the way that they mathematically represent that particular part of their model. As long as a model correctly describes the important features of the atmosphere, then simplifications of other features don't make that model 'wrong', but they do limit how accurately it can reflect climate change; and the different formulations by scientists also explain why there is not universal agreement about the extent of CO_2-induced temperature rise.

As well as deciding exactly which equations to use, a modeller must also choose between an 'equilibrium' and 'transient' experiment. In an equilibrium experiment, a solution is sought to the question of how much warmer the climate will be for, say, a doubling of CO_2 when it has reached equilibrium with the whole ocean (as well as the atmosphere) warmed throughout its depth. In a transient experiment, the question posed is different: how will climate change as the CO_2 gradually increases and the ocean slowly warms from the surface downward? The difference between the two can be illustrated by analogy with the problem of heating a kettle from cold on a small fire, not capable of boiling the water. The ultimate temperature achieved, the 'equilibrium' temperature, will depend mainly on the mean heat output of the fire and the external thermal conditions (radiation, temperature, wind). However, the transient problem - how long the kettle takes to reach this temperature - is also important, and this will depend on how quickly the fire approaches its maximum output (analogous to the increase in CO_2), and on the thermal inertia of the kettle, which depends on the amount of water (analogous to the ocean's thermal inertia). An important factor in the climate problem is the efficiency with which heat is mixed downward from the ocean surface; the more efficient this mixing is, the slower will be the warming of the ocean surface and of the atmosphere in contact with it, but the faster will be the approach to the equilibrium state in which the whole ocean has been warmed to its equilibrium temperature.

The important point is that transient and equilibrium models must be viewed as complementary, and all results viewed with professional scepticism until checked and rechecked. The following sections identify those predictions which find broad agreement across a range of models and in which we can place some confidence.

3.1 Equilibrium models:

Many experiments have been made with climate models, mostly to find the equilibrium response to, say, a doubling of CO_2. Because of the large heat capacity of the deep ocean, it takes very large computing resources to run a coupled atmosphere-ocean model long enough to reach equilibrium.

A simpler and less expensive technique is to use a model which includes only the atmosphere, land and an ocean consisting of a single static layer of thickness about 50 m, which is sufficient to represent the seasonal variation of the ocean's near-surface temperature.

The basic response of such a model is a warming of the earth's mean temperature by about 1.2°C for a doubling of CO_2. However, as climate evolves, associated changes may enhance or limit the response.

Water vapour in the atmosphere will increase as temperature rises (we expect relative humidity to be similar to that we experience today); as water vapour is also a greenhouse gas, this enhances the warming. Snow and ice cover will diminish; by decreasing the reflectivity of the surface this also enhances the warming. Inclusion of the water vapour and snow/ice feedbacks increases the response to about 2.2°C.

Clouds, on the other hand, can either enhance or diminish the warming, giving a total response of 2 to 5°C, depending on how they are represented within the model. Such a result underlines the key nature of the role played by clouds in climate change predictions.

Table 1 lists the predictions of four equilibrium models, published around 1986. All the models include the feedback mechanisms discussed above, but none of the cloud representations is very

Table 1. Predictions of four models for the equilibrium atmospheric atmosphere response to a doubling of CO_2

	GFDL	GISS	NCAR	MO	UNITS
a) Warming					
Global average	4.0	4.2	3.5	5.2	°C
Eastern UK (Jun-Aug)	5.0	4.0	4.0	5.0	°C
Eastern UK (Dec-Feb)	5.5	4.0	6.0	6.0	°C
b) Precipitation					
Global average	+9%	+11%	+7%	+15%	%
Eastern UK (Jun-Aug)	0--1	0--1	0-+1	0-+1	mm/day
Eastern UK (Dec-Feb)	0-+1	0-+1	0-+1	0-+1	mm/day

GFDL = Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA.

GISS = Goddard Institue for Space Studies, New York, USA.

NCAR = National Center for Atmospheric Research, Boulder, Co, USA.

MO = Meteorological Office, Bracknell, United Kingdom.

sophisticated. Given the complexity of the problem, the models show generally good agreement, predicting a global, annual average warming of between 3.5 and 5.2°C.

Other ranges commonly quoted are a little lower. The Villach Conference in 1985 (see Bolin et al, 1986) suggested a range of 1.5 to 4.5°C; Dickinson (1986) estimated that there was a 90% probability that the actual warming would lie between 1.5 and 5.5°C, leading to this slightly larger range being quoted in recent discussions.

The local response may vary considerably from this global mean, but for western Europe, the average changes predicted by these models at equilibrium are close to the global mean changes in summer and are about 20% greater in winter. Globally averaged precipitation increases in all the models, on average by about 10%. An increase in precipitation is obtained at middle and high latitudes, particularly in winter. For the British Isles, the models are in agreement in predicting an increase of between 0 and 1 mm/day in winter. Since the current mean is about 2 mm/day, this is reasonably similar to the globally averaged change.

However, there is little agreement for the British Isles in summer, some predicting increases, others decreases. With higher temperatures, the atmospheric capacity for water vapour would be increased by 7% for each 1K warming; this would be expected to lead to correspondingly more intense rainfall events.

Recently, further experiments have been run with the Meteorological Office model (Ingram 1989). More sophisticated representations of cloud processes have been used than for the Met Office model in Table 1; in one case the different behaviour of ice crystal and water droplets was included and the radiative properties of clouds were allowed to depend on the amount of water or ice estimated to be in the clouds. It must be stressed that these dependencies are quite uncertain and the cloud schemes are still being developed, but

the results are useful in demonstrating the uncertainty in present estimates. The global heating was much smaller, only about 2°C for a doubling of CO_2 in the second experiment rather than 5°C. The reduction of warming was most marked in regions where clouds were part ice crystals, part water droplets, notably over the middle latitude oceans and adjacent land downwind, including western Europe, where the warming was reduced to less than 2°C.

3.2 Transient models

The models considered above try to simulate a new equilibrium state but in practice, as discussed earlier, this is not realistic; the gases will increase gradually and the ocean will respond only slowly and moreover at different rates in different places depending upon the depth of mixing. Consequently, it is expected that the lag in ocean warming will also vary geographically; together with the contrasts between ocean and land responses, these variations may dominate the regional response to greenhouse warming over the next few decades. Other slowly responding parts of the climate system, such as sea-ice and land-ice, may require consideration in this context.

Recently, Hansen et al (1988) have modelled the time-dependent response to a gradual increase in trace gases, using three alternative scenarios for future increases in concentrations. The ocean was represented in their model as a mixed layer, coupled diffusively to an inert deep ocean. ('Inert' in that this deep part of the ocean acts only as a large source or sink of heat; it has no deep ocean currents which can themselves carry heat).

Noting that volcanic eruptions have been regular features throughout history, Hansen et al also incorporated the cooling effect of a major eruption every 10-20 years.

The experiments were started at 1958 levels of trace gases and compared with the 100-year means for a parallel experiment in which

trace gas levels remained constant. This allowed greenhouse effects to be identified separately from any other causes of climatic fluctuation. Hansen et al show results mainly from their intermediate scenario, for which total forcing due to increases in trace gases at 2030 is some 25% below the most widely used estimates of future trace gas concentrations. The global mean warming relative to the control is about 0.4K in 1990, 0.9K in 2010 and 1.4K in 2030. The absence of any acceleration of the warming can largely be attributed to assuming progressive reductions in emissions of trace gases.

Hansen et al's maps show that the changes over Britain are similar to the global means. This suggests that the regional changes in heating (e.g. between land and sea) and any changes in circulation arising from them together have little effect on temperatures over Britain in this experiment. This might not be true in all models. As in other low resolution models used so far for greenhouse gas experiments, the simulation of flow patterns is not as realistic in Hansen et al's model as it can be in some higher resolution models.

There are reasons for supposing that the climate of the British Isles may be relatively slow to respond, because of the proximity of the Atlantic Ocean for most of which any heat gained in summer is deeply mixed each winter. This supposition is given some support by the observed data on atmospheric warming trends between the 1960s and the 1980s as analysed by Karoly (1987 and personal communication). His trends show that a warming had occurred at most stations in the northern hemisphere except around the north Atlantic north of about 45°N, and the northwestern Pacific at 30 to 50°N, where deep winter mixing also occurs.

3.3 Summary of model predictions regarding temperature rise.

Model simulations of enhanced greenhouse warming suggest the following conclusions:-

a) Mean global temperature will increase, by from 2 to 5°C at equilibrium for a doubling of CO_2.

b) The magnitude of the increase over the next half century will lie between 1 and 2°C.

c) The equilibrium warming is likely to be most evident in the mid- to high-latitudes of both Northern and Southern Hemispheres.

3.4 Other predictions from both equilibrium and transient models.

3.4.1 Rainfall

The best estimates of changes in rainfall over Britain are that at equilibrium an increase of order 5 to 15% may be expected in annual totals, with most of the increase concentrated in the winter half of the year. However, not only is this estimate subject to large uncertainties, but it may have little relevance to the transient response, (i.e. the changes to be expected over the next 50 years or so) when the system is far from equilibrium, and the changes may be dominated by natural variability or by regional variations of atmospheric circulation due to uneven warming of the land and different parts of the oceans.

Rainfall records over the past century show that even 20-year averages of seasonal rainfall can vary by 10-15% making any underlying shifts of plus or minus a few percent in long-term average rainfall very difficult to detect. Rainfall changes associated with global warming may increase the variability to 20%.

3.4.2 Humidity

Model results suggest that relative humidities will not change systematically. However, evaporation rates are governed by the humidity deficit below saturation, which depends not only on relative humidity but also on temperature. Humidity deficits will increase by about 7% for each 1°C rise in temperature.

3.4.3 Windspeed

Nothing has been said so far about wind strengths. There has been some tendency for mean wind speeds to decrease in equilibrium simulations. However, as the next few decades are likely to be dominated by transient effects, this may not be very relevant. We are not yet able to predict the likely circulation changes in this phase of a warming.

3.4.4 Solar radiation

It is not obvious that solar radiation will increase or decrease with a greenhouse warming. Clear sky solar radiation is expected to decrease slightly (about 1% for a 2°C warming) due to increased absorption by atmospheric CO_2 and on the other hand some increase might be expected due to decreased cloudiness if soil moisture deficits limit evaporation and so dry the air (see below), whilst increased cloudiness and decreased solar radiation could result from increases in the proportion of clouds composed of liquid water rather than ice.

4 Possible impacts on agriculture in the UK

4.1 Sea Level

Knowledge of climate change becomes academic if the land is under three feet of sea water, and the biggest concern of many east coast farmers is about sea level.

The sea level rise due to a given warming is due partly to thermal expansion of the oceans and partly to the melting of continental icesheets and mid-latitude glaciers.

There have so far been no computer experiments that simulate full ocean mixing and warming in three dimensions, but the effects of the thermal expansion of the oceans may be estimated from a one-dimensional model, as reported by Wigley and Raper (1987). Their model shows a sea level rise of 7 to 9cm for a 1°C surface warming. With a warming of 1 to 2°C, this implies that the thermal expansion alone could raise sea levels by from 7 to 18cm by 2040.

Some further increase is to be expected from the melting of continental ice sheets. This is difficult to assess because some melting of middle latitude glaciers and the Greenland ice sheet may be offset by accumulation of ice on Antarctica in a moister climate; Antarctica is thought to be still too cold for substantial melting, though account must be taken of the effects of a warmer ocean in eroding the margins of the ice shelves.

One crude method of allowing for melting of land ice is to extrapolate from the rises of sea level and temperature observed to date. Estimates in Gornitz and Lebedeff (1987) suggest there was a rise of sea level of about 10cm from 1900 to 1980; associated with a warming of about 0.4°C this suggests that a warming of 1 to 2°C from 1990 to 2040 would raise sea levels by a further 25 to 50cm. This is slightly above the result (17 to 45 cm) obtained by noting that ocean thermal expansion from 1900 to 1980, estimated at about 4cm by

Wigley and Raper (1987), accounts for only a little less than half the observed rise, and assuming that a similar fraction continues to be due to melting of land ice. To this estimate should be added any local change in sea level relative to the global mean due to mantle changes, such as the observed tendency for S E Britain to sink and N W Britain to rise (Rossiter, 1967).

The conclusion of this section is that global sea level rise from the present to 2040 is likely to be in the range 20 to 50cm. The lower end of this range is appropriate for the smaller positive feedbacks and the lower scenarios for greenhouse gas increases.

4.2 Temperature distributions

To interpret predictions of global warming in terms of the likely impacts on agriculture inevitably takes us into realms of speculation, but we want to keep that speculation as firmly rooted in reality as possible. The models do not indicate major changes in day-to-day weather; therefore life in a changed climate is best visualised by superimposing, onto the mean effects predicted by the models, levels of variability that are characteristic of the present climate. In order to look in detail at what might occur at farm level in given circumstances, we have chosen for illustration data from real sites in the UK. It is worth emphasizing that this is purely for illustration; climate models cannot and do not make site-specific forecasts of future climate. The models so far used for climate change experiments work on the basis of areal averages covering over 100,000 square kilometres, which is similar to the area of the British Isles.

Fig 2 shows frequency distributions of January minimum and July maximum temperatures based on data from Woburn for the period 1959-87. The two distributions are skew but in the opposite senses, January minima having a long cold tail, and July maxima a long warm tail. The largest changes in absolute frequency can be expected where the profiles are steep; thus a warming of 2°C would

greatly reduce frequencies of July maxima between 16 and 18°C, with a lesser but still large increase in days with 22 to 25°C. The frequency of maxima of 27.5°C or above would increase from 5 to 10% of days.

Because of the broader and weaker peak, changes would be less sharp in January minima, with the largest change a decrease in minima of around -2°C. However, for winter minima, the most important consideration might be the frequency of frosts; changes in frequency of events below a particular threshold are largest where the threshold is near a maximum in the frequency distribution. There is a maximum just above freezing point, so a warming would reduce January frost frequency quite quickly; for a 2°C warming, the frequency of frosts would decrease by over one third, from about 40 to 25% of 24 hr periods. The probability of severe frosts would be approximately halved: 5% for minima less than -5°C, compared to 10% now: 1% for minima less than -10°C compared to 3% now.

An analysis similar to the above for winter maxima shows that maxima near the snow/rain threshold are also near a peak in the distribution so that warming could markedly reduce snowfall frequencies.

4.3 Growing season

The simplest method of calculating changes in growing season is to shift all temperatures upwards by a constant amount equivalent to the predicted change in mean annual temperature. 'The Agricultural Climate of England & Wales' (MAFF, 1984) defines the start of the growing season as the date on which average 30 cm soil temperature, $T_s(30)$ exceeds 6°C. The effect on growing season of a shift in soil temperature depends on the rate of change with date of $T_s(30)$ around the critical 6°C mark; areas with a <u>more</u> rapid rate of increase of $T_s(30)$ will show a <u>smaller</u> change in the start date of the growing season.

Fig 3 shows the effect of an average +2°C mean temperature rise on the start date of the growing season, based on calculations of the rate of change of $T_s(30)$ by Drinkwater (1977). Across the country, earliness ranges from just over two weeks to just over three weeks. Within this relatively narrow range the only underlying trend seems to be for the effect to diminish with increasing distance from the coast; there is no indication of any effect of latitude.

The extent to which this earliness might be utilised will, of course, depend on the effects of any changes in winter rains; spring operations are very critically dependent on rainfall in April and May - even a slight increase in spring rain could seriously disrupt springtime cultivations and make it difficult to capitalise on the higher temperatures and increased CO_2.

4.4 Evaporation and soil moisture

Evaporation is controlled by sunshine, windspeed, humidity and temperature. In the UK, and particularly in winter, humidity and temperature are the more important variables (Field, 1980).

Table 2 lists, for a site in the East Midlands, the increase in monthly potential evapotranspiration PT that would result from a uniform increase in air temperature of +2°C. Relative humidity is unchanged from present levels. For the year as a whole PT is up by 9% to about 700mm. About one quarter of the 60mm annual increase is attributable to the winter months.

The impact of increased evaporation depends critically on rainfall, since the combination of the two determine the amount of water reaching field drains, the maximum soil moisture deficits reached during the summer (and by implication the amount of irrigation required) and the dates of leaving and entering field capacity. We consider three scenarios: (a) rainfall unchanged from the present (b) annual rainfall increased by 20% and (c) annual rainfall reduced

by 20%. Note however that (b) and (c) are quite extreme scenarios and that the models cannot yet reliably predict which, if either, is the more likely.

Figs 4a, b, and c present the annual progress of PT minus Rainfall for the three scenarios; in each the present average pattern (unchanged rainfall, unchanged temperature) is included for reference. It is important to remember that these are climatic comparisons which assume (i) continuously cropped surface (ii) actual evapotranspiration (AT) equals PT. The spring situation is most likely to represent actual conditions for grass and autumn sown crops which cover the ground. The rest of the curve is likely to be a better representation for deep-rooted crops on soils with high available water capacity, rather than crops harvested in late summer with several weeks of bare soil.

Fig 4a shows that field capacity ends a few days earlier for increased PT, which implies that where excess soil moisture does not currently limit the start of field operations, some or all of the expected earlier start of the growing season (Fig 3) could be usefully exploited. Over the early part of the growing season values of soil moisture deficit (smd) diverge only slowly, the two traces remaining within 25mm (1 in) till mid-July. Beyond this point differences of up to 45mm develop by the end of October, and the return to field capacity is considerably delayed, by around five weeks. The excess of annual precipitation over PT is substantially reduced, from around 70 to around 10 mm.

Fig 4b analyzes the effect of annual rainfall increased by 20%. Two situations are depicted; (1) every month has a 20% increase in rainfall and (2) the 20% increase in the annual total arises entirely from a 40% increase in winter (Oct-Mar) precipitation. Departure from field capacity occurs a few days either side of the present curve. Like Fig 4a, in the early part of the growing season there is little change in the pattern of smd, which till mid-July remains within 25mm (1in) of the present regime. Only after July

do the traces diverge substantially, with trace 2 reaching a maximum deficit of around 200mm. (For simplicity, no account has been taken of the effect of increasing smd on actual AT as opposed to potential evapotranspiration; in reality, and in the absence of irrigation, AT would diminish, and smd increase more slowly, beyond deficits of typically 50-130 mm depending on rooting depth, etc).

Both 1 and 2 have returned to field capacity by early January, about two weeks earlier than the present climate graph.

Fig 4c depicts the situation that out of the three considered would pose the most serious problems for agriculture. Even under present levels of evaporation, a 20% drop in average annual rainfall would preclude (for this particular site) full groundwater recharge during the winter. With PT increased by a warmer climate, soil moisture would become a limiting factor for many operations.

The worst case of the two shown in Fig 4c is where the reduction in rainfall was concentrated in the summer months (Trace 4), when smd might potentially reach almost three times present levels. Put another way, an average three-fold increase in irrigation capacity would be required to keep crops free of water stress. In practice actual evaporation over large areas would fall well below PT, as natural vegetation died back and as conservation measures were implemented to limit moisture loss. This would lead to drier air, so that those crops freely supplied with water would face an even greater evaporative demand.

4.5 Pest Problems

Warmer conditions will inevitably encourage a greater number of pests and diseases, both because the higher temperature will favour more rapid development and an increased number of generations, and because milder winters will permit greater winter survival.

While much insect development depends almost linearly on temperature there are some non-linearities which complicate the situation namely diapause and the discrete cycles of production (Crawford et al, 1989).

Many insects respond to falling temperatures and decreasing daylength by entering a period of suspended animation - the diapause - which prepares them for overwintering. In many species a period of cold is required to 'break' the diapause and, until this condition is satisfied, the insect will not respond to the rising temperatures of the following spring. For such insects, warmer conditions will result in earlier spring emergence only if conditions for end of diapause are fulfilled.

Some insects which cause damage in the south may not normally be a problem further north because lower temperatures limit their development and number of generations. Warmer conditions may encourage the northward extension of some pests, but the relationship between pest numbers or damage may not increase linearly with temperature unless the additional generation(s) are able to complete their development before falling temperatures or decreasing daylength initiate diapause.

The effects of warmer conditions may be most marked in aphids where shorter generation times will allow more rapid adaptation to the changed climate. This may be particularly so in aphids which overwinter as adults - eg M. persicae. Decreased frost frequency may allow greater numbers to survive the winter, although winter rainfall is also an important factor. More generations, from a higher number of winter survivors and an earlier start to spring activity, may well lead to greater problems with viruses of potatoes and sugar beet. Many of the cereal aphids may also increase - observe the aphid problems being faced in this current year!

Warmer and drier summers will affect the survival and depredations of cutworms - A. segetum. A general return to the damage levels of 1975-76 is probably unlikely but such levels may well occur more frequently than in the past.

The warming which may encourage the northward extension of pest risk within the UK may similarly allow the introduction of new pests which have been active in parts of Europe. Some insects, which in the past have been only occasional visitors, may become more common as their natural habitat moves northward and closer to our shores. Some exotic pests, at present able to survive only in protected environments or during periods of exceptional weather, will be more likely to be able to survive in the open and cause damage to field crops.

The introduction of new crops, more suited to the changed climate will probably also result in the introduction of new pest species but may also inhibit the survival of some existing pests which are specific to our traditional range of crops.

It should be remembered that the changed conditions may also work to the advantage of those insects and other organisms which at present act to limit the development of some pest populations by disease, predation and parasitism. Once a new population balance is achieved, it may be found that some pests are then better controlled by natural factors.

4.6 Crop production

4.6.1 Direct effects of increased CO_2

Glasshouse growers derive economic benefit by boosting CO_2 levels, and laboratory experiments show marked increases in photosynthetic rates with increased CO_2 concentrations: up to 30% increase for doubled CO_2. However there is evidence that higher global levels of CO_2 will not produce corresponding yield increases in field crops.

Plants seem to acclimatize in time to the increased levels such that the overall effect of doubled CO_2 on yield would be relatively small. For cereals the increase in temperature accompanying the increase in CO_2 would oppose the beneficial effects: it has been estimated that a 3 to 4 deg C rise in mean temperature would exactly cancel the yield benefits of increased CO_2 (DOE, 1988).

Stomatal conductance in general falls as CO_2-concentration increases, reducing evapotranspiration, and it does seem that for field crops less water would be required per unit of dry matter produced.

4.6.2 Effects of increased mean temperature

Determinate crops such as cereals, which pass through a fixed series of growth stages according to elapsed degree-days, are likely to show reductions in yield quite apart from any effects of water stress. By going through growth stages at a faster rate, the time available for conversion of sunlight into dry matter will be less, even though in the early season light interception will be improved by earlier attainment of full leaf cover. (This effect is currently demonstrated by the consistently higher barley yields obtained in Scotland compared to say, East Anglia). However breeding for, or a change to, later-maturing varieties can be expected to compensate for this effect, and it is more likely water availability that will be the more important factor in cereal yields.

Crops such as potatoes or sugar beet, which remain in a vegetative state throughout their productive life, should on the other hand show increased yields - again, as long as water is not limiting. Warmer conditions will permit earlier planting, and with more rapid leaf development in the early spring this should result in greater utilisation of the high levels of radiation in May and June.

It is tempting to suggest that higher spring temperatures will benefit top and soft fruits through a decrease in late spring frosts, but a detailed analysis of the effect of a 2°C warming on budburst and frost damage (Cannell and Smith, 1986) indicated that although budburst would occur earlier, average temperatures at budburst would be similar to the present, and risk of subsequent frost damage would be increased.

5 Summary

The estimated global mean warming by 2030, allowing for the ocean's thermal inertia, is about 1.2 to 2°C from mid 19th century levels, while by 2050 a further warming of up to 1.3°C is anticipated for typical estimates of greenhouse gas concentrations. The warming from present values may be obtained by subtracting the warming so far observed, about 0.5°C. In this paper we have looked at the effects of a 2°C rise from present day values. However, it should be noted that the ultimate warming achieved when the ocean and atmosphere have reached equilibrium with increased greenhouse gas levels could be larger by as much as a factor of two. The local response may vary from these global means; for western Europe, there are reasons to suppose that the proximity of a deeply mixed North Atlantic may retard the warming. Because of the shape of the frequency distributions, a marked decrease in frost and snow frequencies is to be expected. Though gale frequencies are likely to change, due to the responses to ocean and land temperatures, little can yet be said about the nature of the changes.

An increase in global sea levels has been observed over the last century with some acceleration in recent decades. This has been attributed to thermal expansion of the oceans together with melting of glaciers and ice sheets. The estimate of the rise over the next few decades is considerably affected by how sensitive the climate is; over the next 40 years, a rise of 15 to 40cm appears likely. However, the uncertainty as to the response of the ice sheets is large. It must be stressed however that at equilibrium (which would

not be reached for many centuries) the thermal expansion effect is much larger than in the transient response; if the whole ocean warmed by 5°C, the sea level rise from thermal expansion alone would be over 3 metres.

In this paper we have considered a very simple scenario - a 2°C rise in mean annual temperature, but with relative humidity, sunshine and windspeeds maintained at present levels. In this scenario the growing season would begin 2-3 weeks earlier than at present over most of the country. Warming will alter the potential yield of crops presently grown in the UK, but where potential yield is diminished the introduction of new varieties is likely to compensate. The profile of pests will certainly change but it is not possible to predict any details beyond a general northerly movement of existing species.

In the particular case study of the East Midlands the frequency of slight frosts would diminish, but the possibility of occasional severe frosts would remain. Annual average potential evaporation would increase by about 60 mm; under the present rainfall regime this change would be significant, but with average rainfall still exceeding average potential evapotranspiration, agriculture would remain on the whole 'rain-fed'. If, however, this increase in evaporation were to be combined with a reduction in total or seasonal precipitation, then the implications for rain-dependent crops would be serious. Unfortunately future rainfall patterns are among the aspects of climate change least confidently predicted by climate models and, to be more certain as to precisely how our agricultural climate will evolve, we have little choice but to await the unfolding results of the painstaking and sophisticated research now in progress.

TABLE 2

Changes in average monthly potential evapotranspiration (PT) for a mean temperature rise of 2 deg C.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
New mean temp (deg C)	5.3	5.4	7.3	9.7	13.1	16.3	17.7	17.6	15.4	12.4	7.9	5.8	
Mean rel humidity (%)	90	89	82	80	77	76	77	80	83	87	89	91	
New PE (mm)	15	17	43	66	98	115	114	96	66	38	20	13	701
Present PE (mm)	13	16	39	61	90	106	105	89	61	34	17	11	642
Increase in PE (mm)	2	1	4	5	8	9	9	7	5	4	3	2	59
Present rainfall (mm)	65	55	50	50	55	55	60	80	60	55	70	60	715

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Figure Legends

Fig. 1 Global surface temperature relative to 1950-79 average (based on Jones et al, 1988).

Fig. 2 Probability distribution for (a) January minimum and (b) July maximum temperatures (based on smoothed data from Woburn, Beds).

Fig. 3 Earliness of start of growing season caused by an average 2 Deg C increase in 30 cm soil temperatures.

Fig. 4 Mean annual progress charts for potential soil moisture deficity (PT minus rainfall) and for drainage into soil (rainfall minus PT) with evaporation increased by 2 Deg C warming. (Based on data from Watnall). AAR = Average Annual Rainfall.

Figure 1

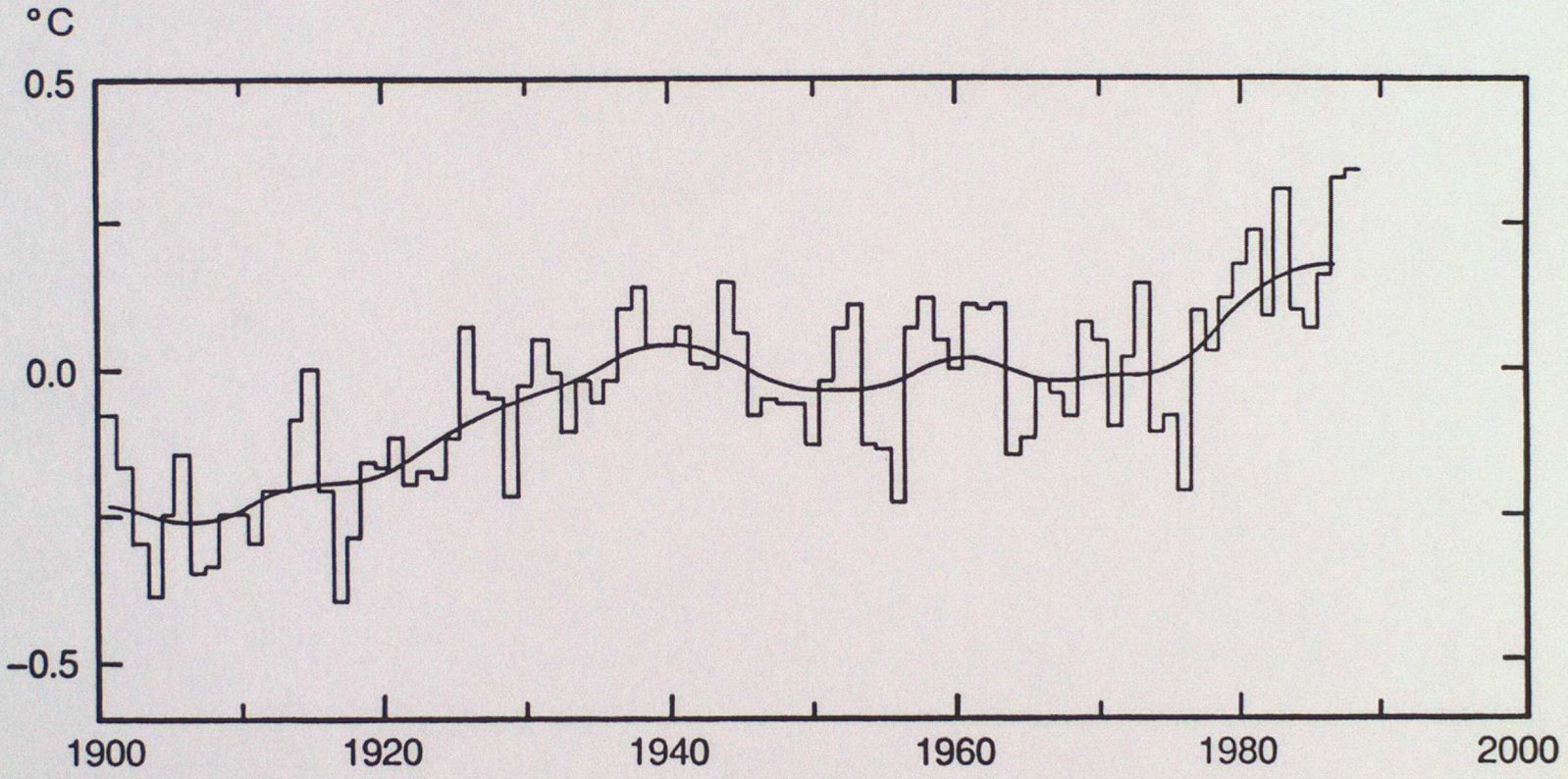
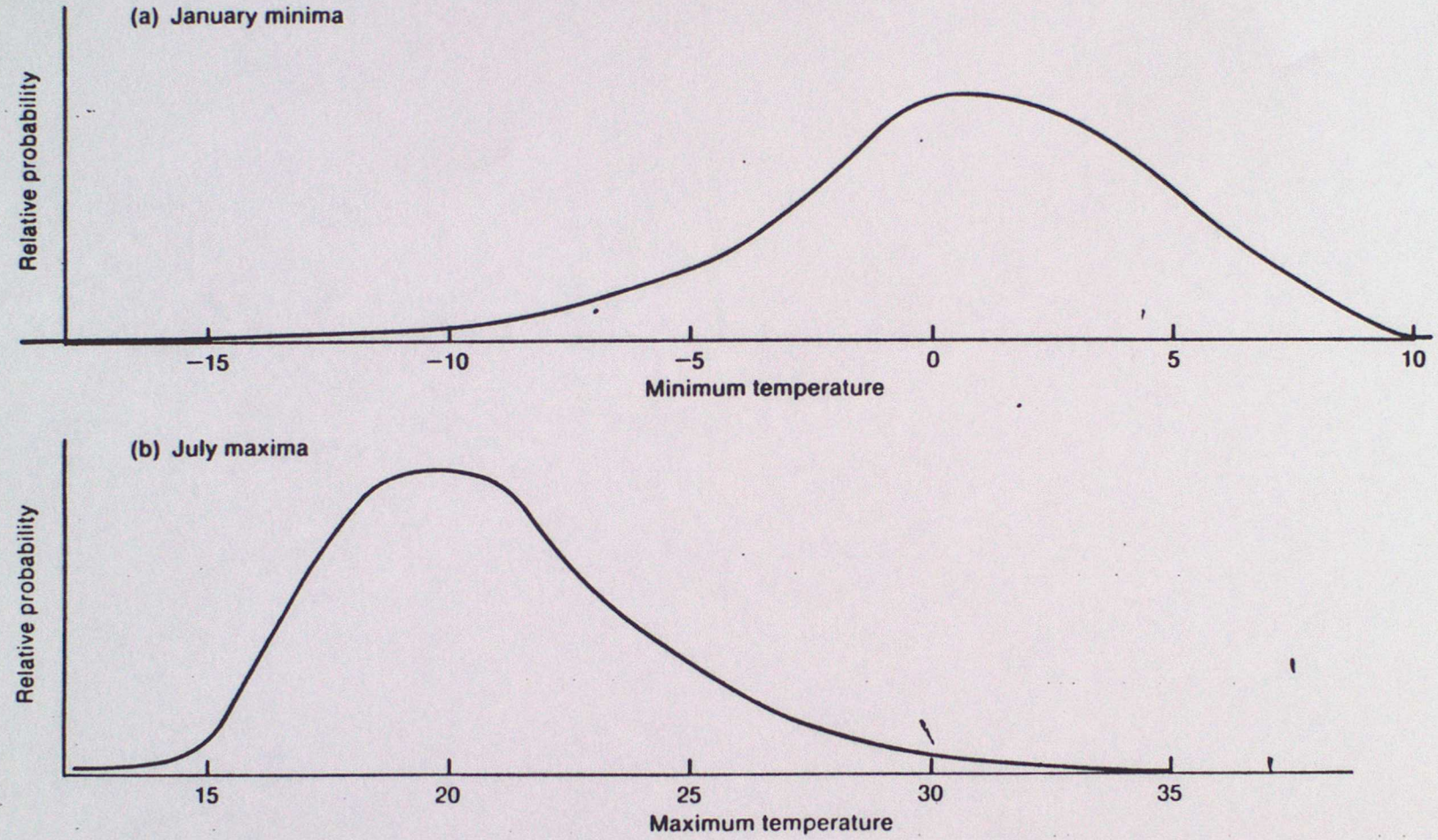


Figure 2


(a) January minima
Relative probability
−15
−10
−5
0
5
10
Minimum temperature
(b) July maxima
Relative probability
15
20
25
30
35
Maximum temperature

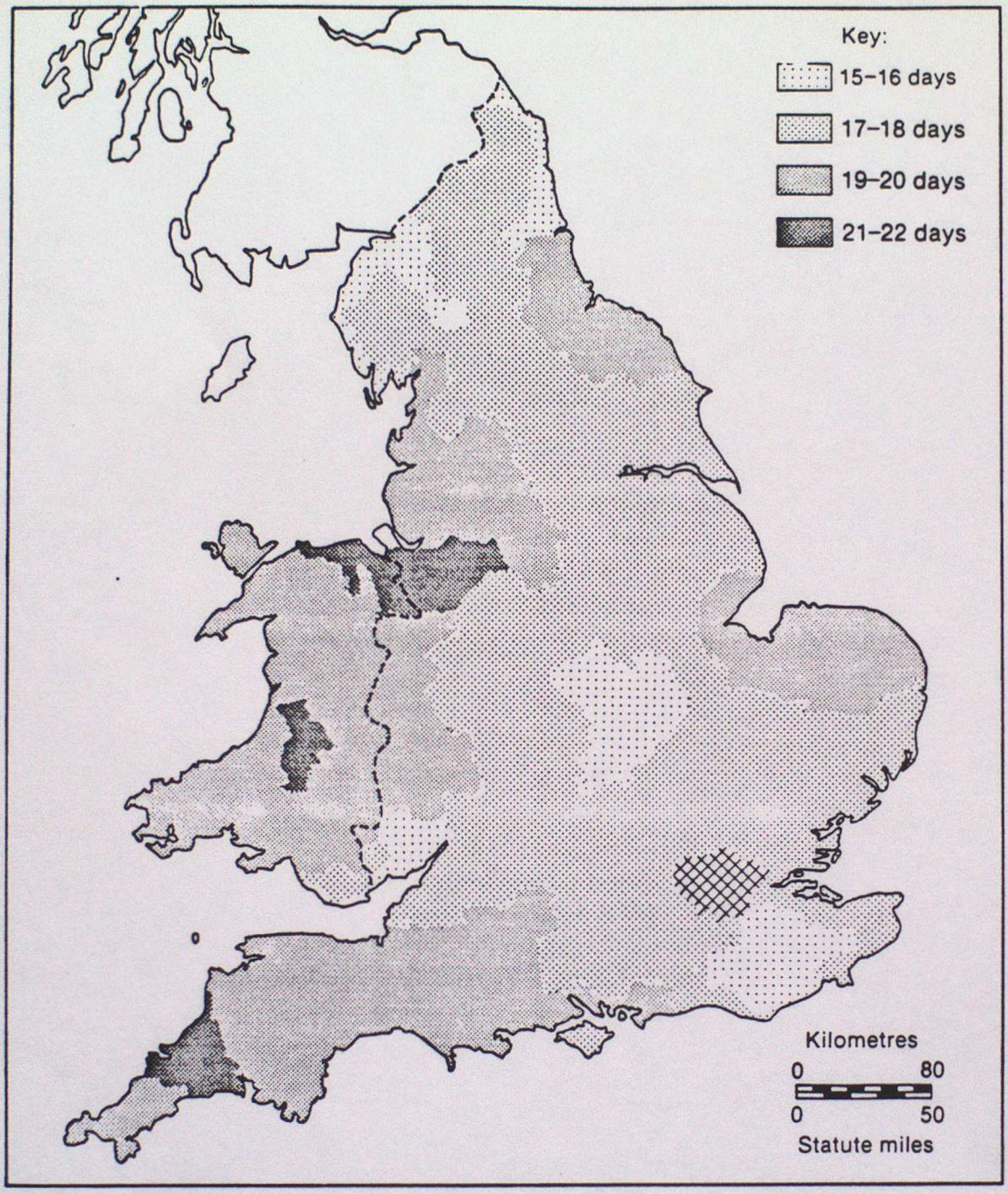

Key:
15–16 days
17–18 days
19–20 days
21–22 days
Kilometres
0
80
0
50
Statute miles

Figure 3

Figure 4

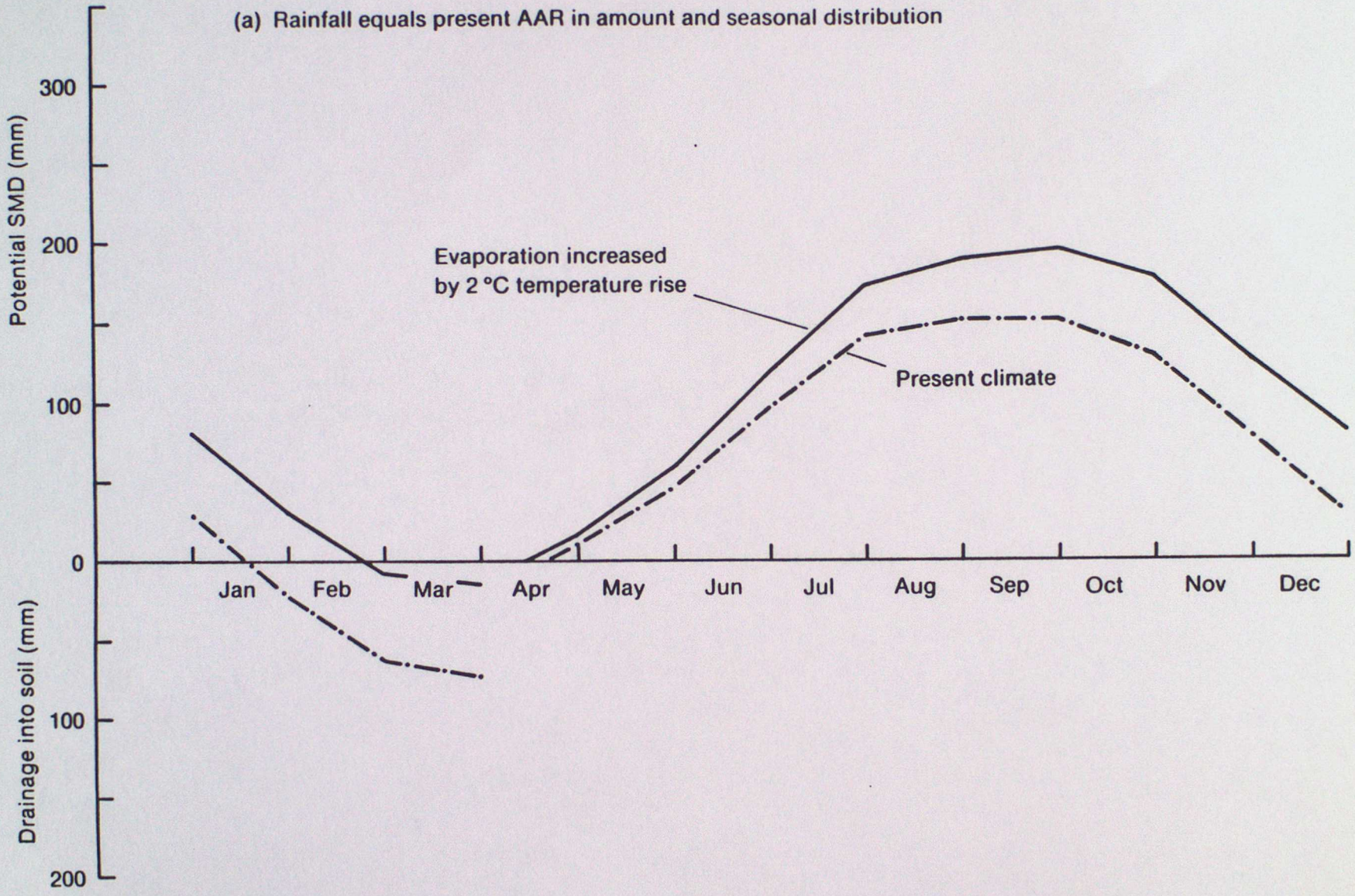

(a) Rainfall equals present AAR in amount and seasonal distribution
Potential SMD (mm)
300
200
100
0
100
200
Drainage into soil (mm)
Evaporation increased
by 2 °C temperature rise
Present climate
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 4

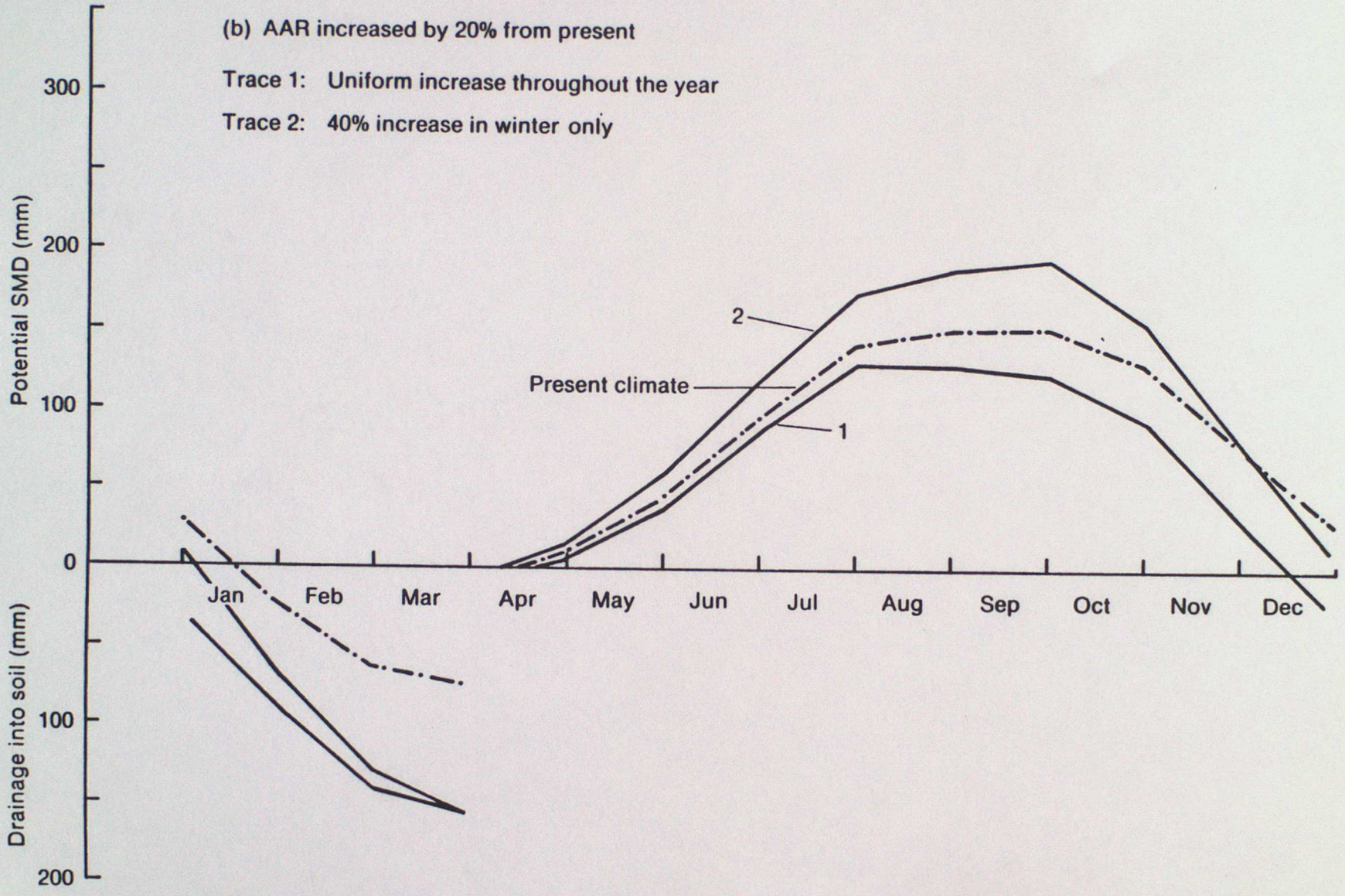
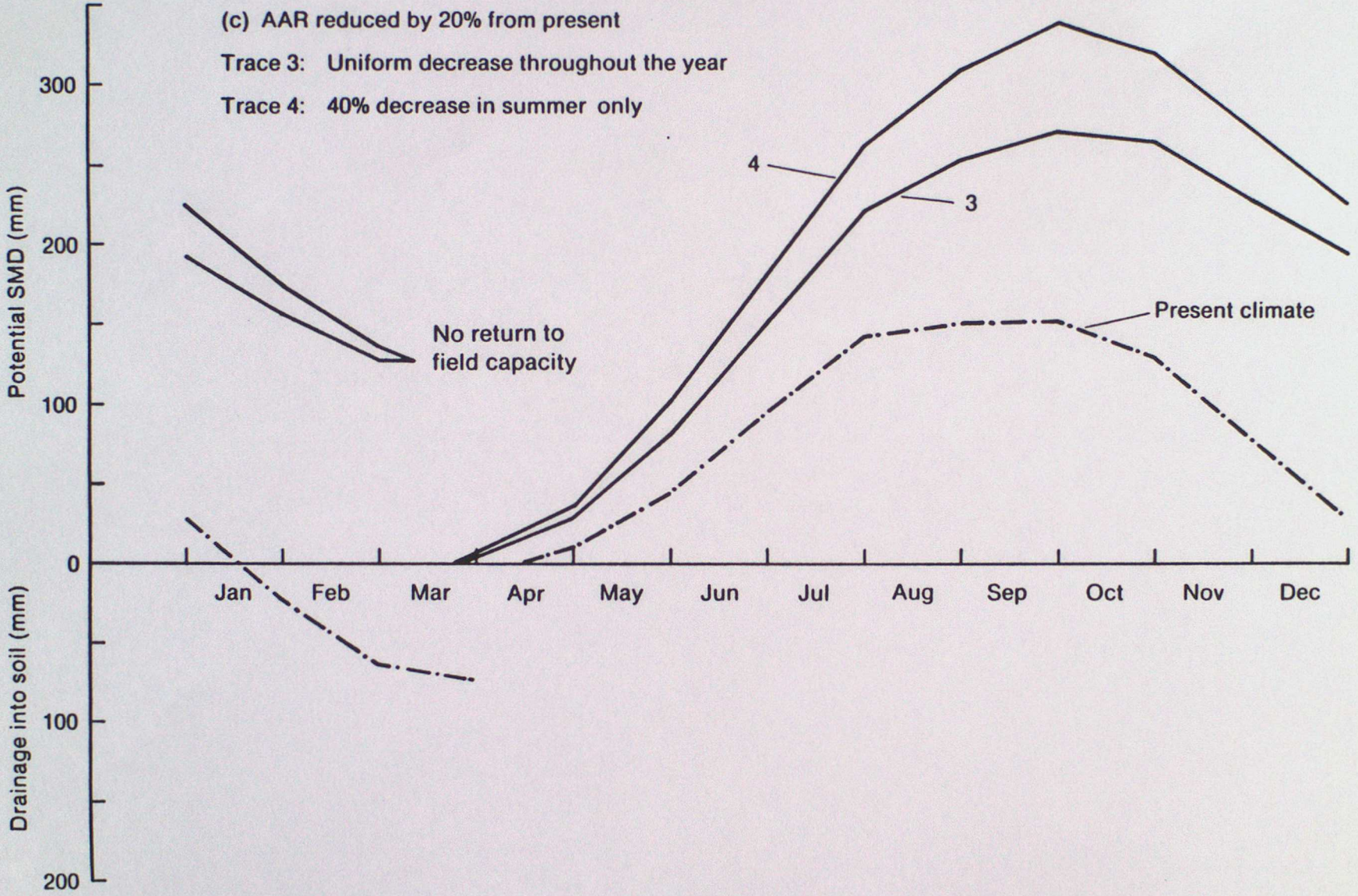

(b) AAR increased by 20% from present
Trace 1: Uniform increase throughout the year
Trace 2: 40% increase in winter only
Potential SMD (mm)
300
200
100
0
Drainage into soil (mm)
100
200
2
Present climate
1
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 4


(c) AAR reduced by 20% from present
Trace 3: Uniform decrease throughout the year
Trace 4: 40% decrease in summer only
Potential SMD (mm)
300
200
100
0
100
200
Drainage into soil (mm)
4
3
Present climate
No return to
field capacity
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

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